Dynamic Analysis of Vanadium Redox Flow Cell System Integrated Into Solar Power Plant in Türkiye

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Countries increasingly favor renewable energy over conventional sources due to concerns about energy security, environmental sustainability, and zero-emission targets. However, the inherent variability and fluctuation of renewable energy source supply can cause grid power and frequency instabilities.To address this, battery energy storage systems are commonly integrated with renewable energy systems, and Vanadium Redox Flow Batteries (VRFB) stand out due to their long cycle life, deep discharge tolerance, and advanced controllability. Qazi et al. (2024) studied a VRFB system connected to an 11 kV grid stabilized frequency deviations from 50.1 Hz to nominal levels during load increases [1]. Similarly, Foles et al. (2022) demonstrated that VRFB can reduce sudden solar output drops with ±300 kW interventions and take down inverter ramp rates from 1 MW/min to 0.2 MW/min [2]. These findings highlight VRFBs' role in enhancing grid stability when integrated with renewable energy. Fares et al. (2014) demonstrated that a 1 MW/250 kWh VRFB system could respond within less than 0.5 seconds, successfully regulating frequency deviations within ±0.05 Hz under ERCOT grid simulations [3].

In this study, dynamic analysis of vanadium redox flow battery system integrated into solar power plant in Turkey was modeled and analyzed in MATLAB. The system parameters used in the model were obtained from commercial battery specifications and relevant literature. The open-circuit voltage (Voc) of the battery is calculated using the Nernst equation, based on the concentrations of the redox couples:

$$V_{oc} = E^0 + \frac{RT}{nF} ln\left(\frac{SoC}{1 - SoC}\right)$$

According to this equation, redox couple concentrations are determined based on the State of Charge (SOC) and incorporated into the model. At each step, the terminal voltage (Vt) is calculated iteratively by considering internal resistance and current.

$$V_T = V_{oc} - I.R_{int}$$

The State of Charge (SOC) is updated over time by considering the coulombic efficiency (η):

$$SoC_k = SoC_{k-1} + \frac{I.\Delta_t}{Q_{total}} \cdot \eta$$

To evaluate grid impact, a frequency response model was added. Deviations were calculated with and without VRFB using a sensitivity coefficient (K_{freq}).

Without VRFB: $\Delta_f = K_{freq} \cdot P_{net}$

With VRFB: $\Delta_{fVRFB} = K_{freq} \cdot (P_{net} - P_{battery})$

These deviations were added to the nominal grid frequency of 50 Hz to generate dynamic frequency profiles for both cases. The model evaluates the VRFB system's charge-discharge behavior, terminal voltage (Vt), SOC evolution, pump power consumption, and grid frequency response hourly, driven by the net power difference between solar generation and load. All system dynamics, including the effects of frequency stabilizing on the VRFB, are illustrated in detail in Figure 1.

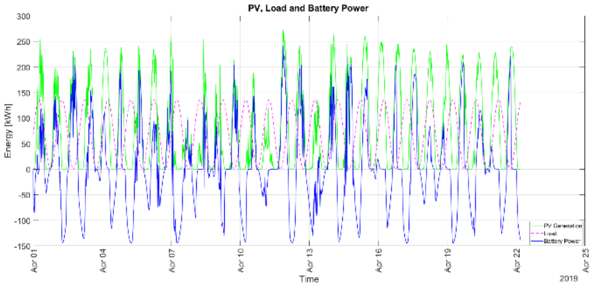

Figure 1. VRFB system impact: PV, load, and battery power

As shown in Figure 1, the VRFB system charges during generation surplus and discharges during deficits, effectively balancing the grid load. Battery current reached ±2000 A, and terminal voltage ranged between 500–560 V. The power difference between PV and load varied from +200 kWh to –150 kWh. Also, in this study, grid frequency remained near the nominal 50 Hz while with VRFB active. These findings confirm that the VRFB system enhances both energy balance and frequency stability in renewable-integrated grids.

References

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Batuhan Mert Laçinkaya is a graduate student in Energy Systems Engineering, focusing on sustainable energy technologies and applied research. He currently works as an R&D Project Engineer, managing TÜBİTAK-supported projects in autonomous robotics and photovoltaic systems. He has received recognition in national technology competitions and contributes to the development of innovative solutions in the energy sector. His background combines academic research with practical engineering experience across multidisciplinary teams.

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